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PEAK DISCHARGE FOR HIGHWAY DRAINAGE DESIGN

by Carl F. Izzard, A.M. ASCE

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PAPERS

PEAK DISCHARGE FOR HIGHWAY DRAINAGE DESIGN

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Synopsis

The use of stream-flow records for determining the size of highway drainage structures is a logical procedure. This paper shows that by developing regional flood curves the peak rate of runoff on a stream can be estimated for a given frequency—whether or not stream gaging records are available for that particular stream. A graph is included that can be used for estimating peak rates of runoff on small watersheds to aid in culvert design.

Introduction

The present (1953) trend for determining the required waterways for bridges is to estimate the peak discharge and stage for some reasonable frequency of flood occurrence, and then to compute the waterway required to pass this flood with an amount of backwater tolerable for the conditions at the site. In the cases where the flood flow is confined between the river banks, the bridge usually causes no appreciable contraction, and the primary concern is getting the superstructure high enough to clear the design flood. More commonly, however, a considerable proportion of the flood flow may be on the flood plain outside of the banks of the main channel. In such cases the total length of the bridge is made less than the width of the flood plain, and may consist of a main channel crossing and one or more relief bridges.

Since a bridge usually costs more per foot than does embankment, the total cost of a valley crossing can be reduced by decreasing the length of the bridge. If the waterway is reduced excessively, however, the increased velocity through the opening may induce dangerous scouring action and the required velocity head may cause excessive backwater. In order to estimate the velocity of flow through the contracted opening and backwater, the design discharge and its corresponding stage in the unobstructed channel must be known. Also the damage likely to be incurred if this flood is exceeded once in a given number of years must be compared with the increased cost of providing an opening

large enough to eliminate or reduce the probable damage.

At the present rate of construction (1953) more than $500,000,000 is spent annually for the construction of bridges and culverts. This amount is not sufficient to meet the demand generated by obsolescence of existing structures caused by increased traffic volumes and increased traffic speeds. To make maximum use of limited funds, it is necessary to be certain that no bridge is built longer than is requisite. Unlike spillways on earth-fill dams, where loss of life as well as destruction of the dam may result if the spillway capacity is exceeded, bridges and roadways can usually be submerged, without material damage. Determination of the frequency of the overflow of a roadway to be tolerated should include consideration of the character and volume of highway traffic, and the length of time traffic is interrupted.

The magnitude and frequency of peak floods are therefore of primary concern to highway engineers. This paper seeks to focus attention on various methods of estimating floods—not only on streams for which discharge records are available, but also for ungaged streams.

Frequency Computations

T. Dalrymple, A.M. ASCE, has shown that when mean annual floods on a group of watersheds having similar hydrologic characteristics are plotted against drainage area the relationship can be approximated by a straight line on logarithmic graph paper.[2] Furthermore, a composite frequency curve can be drawn showing the ratio of the flood of a given frequency to the mean annual flood for any recurrence interval up to the period of record. This curve can also be extrapolated to a limited extent, if it is realized that the probable error increases as the recurrence interval exceeds the period of record. Thus, for ungaged watersheds within the same geographic region, the probable flood for any recurrence interval not greatly in excess of the period of record can be estimated with confidence. The procedure is to determine from a set of curves the mean annual flood corresponding to the drainage area, and then to multiply this by the ratio for the desired recurrence interval.

[2] "Regional Flood Frequency," by Tate Dalrymple, *Research Report 11-B*, Highway Research Board, Washington, D. C., 1950.

The Bureau of Public Roads, United States Department of Commerce (USBPR) applied this procedure with some modifications to particular regions with good results. The USBPR's procedure has been to prepare frequency curves for all stations having sufficient records, and then to plot the 25-yr flood against the drainage area. Watersheds having similar characteristics tend to "line up" on logarithmic graph paper, as will be shown subsequently.

A typical flood frequency curve for the Big Blue River at Randolph, Kans., is shown in Fig. 1. This figure has ruling devised by R. W. Powell[3] M. ASCE, for use with E. J. Gumbel's theory of extreme values.[4] Application of this theory requires the use of the peak flood for each year of record. The floods are tabulated in order of magnitude beginning with the greatest flood listed as Order No. 1. The plotting position is computed as $\frac{n+1}{m}$, in which n is the

[3] "A Simple Method of Estimating Flood Frequencies," by Ralph W. Powell, *Civil Engineering*, Vol. 13, No. 2, February, 1943, pp. 105-6.

[4] "Floods Estimated by the Probability Method," by E. J. Gumbel, *Engineering News-Record*, Vol. 134, June 14, 1945, pp. 833-837.

the number of years of record and m is the order number. In this case the maximum flood in 30 yr of record was 98,000 cu ft per sec. It is plotted at 31/1 = 31 yr. The next highest flood was 55,400 cu ft per sec and is plotted 31/2 = 15.5 yr. Other floods are plotted in a similar manner. A straight line is then drawn to give the best fit to the plotted points. In Fig. 1 the maximum flood is out of line, and was ignored in drawing the frequency curve on the assumption that its recurrence interval should actually be much greater than the period of record. There is no reason why a 100-yr flood might not have occurred during this period.

W. D. Potter has developed a simplified method of determining the position of the frequency curve. His method eliminates personal judgment,[5] and is

[5] "Simplification of the Gumbel Method for Computing Probability Curves," by W. D. Potter, *SCS-TP-78*, Soil Conservation Service, Washington, D. C., May, 1949.

recommended for use in statistical correlation studies of factors affecting peak rates of runoff.

Frequency curves have been prepared for all stations in Kansas for which there were records for at least 15 yr. The locations of these stations are shown in Fig. 2. A few of the shorter records were extended by establishing a correlation with nearby longer records as described by Mr. Dalrymple.[2] Another method for adjusting short records involves adjusting the peak rates according to a comparison of the rainfall experienced for the short period of runoff record with that for a much longer period. Where long rainfall records are available, it is possible to extend a streamflow record back over the entire period of rainfall record using techniques developed by the United States Weather Bureau, Department of the Interior (USWB), in flood forecasting.

The 25-yr flood read from each frequency curve is plotted against the drainage area (net contributing area) in Fig. 3, using different symbols for each of the several regions. The numbers shown with each point correspond to the gaging station numbers shown in Fig. 2.

Regional Flood Characteristics

Regional Flood Curves.—Three lines have been drawn on Fig. 3 which are applicable, respectively, to various small rivers in eastern Kansas (east of 96.5° west long.), the Big Blue and Little Blue rivers, and the Kansas River tributaries west of Ogden. The dash line is an extension of a line that was found to fit 25-yr floods on small watersheds with mixed cover. This line was partly based on data from the Soil Conservation Service (SCS) Hydrologic Experiment Station at Hastings, Nebr., which is located on the headwaters of the Little Blue River.

Two of the peak runoff curves from the SCS report[6] have been plotted on

[6] "Rates of Runoff for the Design of Conservation Structures in the Central Great Plains of Nebraska and Kansas," by John A. Allis, *SCS-TP-69*, Soil Conservation Service, Washington, D. C., August, 1948.

Fig. 3. The upper curve applies to a watershed where the main channel has no meanders and the lower curve applies to a watershed where the main channel is about 75% longer than the valley distance. It is of interest to note that the curve for the Big Blue and Little Blue rivers is almost directly in line with the latter curve. Stations 33, 35, and 37 in eastern Kansas plot below the line drawn for that region. A probable explanation is that these are all long, narrow watersheds. Another observation is that stations 5, 6, and 7 for the

Arkansas River tributaries plot successively higher as they come closer to eastern Kansas. Station 5 has a magnitude comparable with the Kansas River tributaries immediately to the north.

As noted by R. W. Carter, A.M. ASCE, large rivers in Georgia that cross regional boundaries do not conform to curves established for the separate regions.[7] Station 16 on the Kansas River, not far downstream from the confluence with the Republican River, has a flood magnitude in line with the curve for the Kansas River tributaries. The flood peak increases markedly at station 17 after the Big Blue River joins the Kansas River and continues to rise as the mouth of the river is approached at station 18.

[7] "Floods in Georgia—Frequency and Magnitude," by R. W. Carter, *Geological Survey Circular No. 100*, U. S. Geological Survey, Washington, D. C., March, 1951.

Flood Frequency.—The curves in Fig. 3 can be used to estimate floods of other frequencies by multiplying the 25-yr flood by the following factors:

Frequency, in years	Factor
50	1.2
10	0.8
5	0.6

These factors are median values based on ratios obtained from the individual frequency curves, and listed to the nearest tenth. The maximum range in the ratio was from 0.07 below to 0.05 above the factors listed. It is of interest to note that the same range in frequency factors covers data from Georgia[7] and Minnesota[8] as well as a small group of watersheds in Virginia for which data have not been published, despite wide differences in flood magnitude.

[8] "Magnitude and Frequency of Floods in Minnesota," by C. H. Prior, *Bulletin No. 1*, Div. of Waters, Minnesota Dept. of Conservation, St. Paul, Minn., November, 1949.

Flood Frequency Reports.—The United States Geological Survey, Department of the Interior (USGS), in cooperation with state agencies, has compiled data on flood frequencies by regions for Georgia,[7] Minnesota,[8] and western Washington,[9] following in general methods described by Mr. Dalrymple.[2] In the Minnesota report, however, the mean annual flood was plotted against the product of drainage area in square miles and mean annual runoff in inches. The Washington study includes correlation of peak runoff with several factors.

[9] "Floods in Western Washington," by G. L. Bodhaine and W. H. Robinson, *Geological Survey Circular No. 191*, U. S. Geological Survey, Washington, D. C., 1952.

Regional flood frequency studies in Louisiana have been published (1952) as a bulletin of the highway department and the USGS.[10] Similar studies are in progress (1953) in a number of other states, usually as a cooperative project of the USGS and the respective state highway department. The first bulletin on flood frequencies was published in 1946 by Ohio[11] before the concept of regional flood studies had been established.

[10] "Floods in Louisiana—Magnitude and Frequency," by J. S. Cragwall, Jr., U. S. Geological Survey and the Louisiana Dept. of Highways, Baton Rouge, La., December, 1952.

[11] "Floods in Ohio—Magnitude and Frequency," by William P. Cross, *Bulletin No. 7*, Ohio Water Resources Board, Columbus, Ohio, October, 1946.

Maximum Floods of Record.—Maximum floods of record have been plotted against drainage area in Fig. 4 for the same Kansas stations that are shown in Figs. 2 and 3. The points scatter widely, as might be expected, because each

point has a different frequency. No regional trends are evident except for stations 29, 30, 31, and 32 for the Big Blue and Little Blue rivers where the 1941 floods were uniformly about 1.5 times greater than a 25-yr flood. It is possible that a storm will occur on the Big Blue and Little Blue rivers similar to the 1935 storm that produced peaks illustrated by stations 12, 13, 14, and 15 on the Republican River. Maximum floods on the Big Blue and Little Blue rivers might then approach the magnitude of the Republican River floods or even exceed them. The 1951 flood, however, on the Neosho River (station 11) is so far above the magnitude of any other floods, that a greater flood is a remote possibility. It is of interest to note that newly designed highway bridges, even though submerged, withstood the 1951 Neosho River flood with virtually no damage.

At the other extreme, frequency studies show that two of the maximum floods of record, on the Verdigris River (station 8) and the Marmaton River (station 36) are approximately at the 25-yr flood frequency. Thus, highway bridges built to the maximum high water of record on these two streams would be applicable for only a 25-yr flood.

The regional flood-frequency curves in Fig. 3 are a better guide to economical bridge design than the maximum floods shown in Fig. 4, but maximum floods should be investigated. The highway bridge must be safe against destruction by such a flood, even though the approaches may be overtopped and partially destroyed.

Analysis of Regional Flood Curves.—For ungaged watersheds within a given region, for which a regional flood curve has been developed, the flood curve is a means of estimating the flood magnitudes for recurrence intervals not greatly in excess of the length of the records on which the curve is based. Such an estimate, based on a number of stations, is more reliable than an estimate based on a single record of an adjacent watershed with similar hydrologic characteristics.

Research is needed to discover the factors causing significant differences among watersheds in the same region. Why should points 10, 11, and 39 in Fig. 3 be below the peaks for other watersheds in eastern Kansas? Or why is point 25 relatively high, and point 23 relatively low in western Kansas?

Mr. Potter has demonstrated a solution to the problem in a study of peak rates of runoff from fifty-one watersheds in the Allegheny-Cumberland Plateau.[12] Six of these are experimental watersheds of the SCS and the remainder

[12] "Rainfall and Topographic Factors that Affect Runoff," by W. D. Potter, *Transactions*, Am. Geophysical Union, Vol. 34, No. 1, February, 1953.

are regular gaging stations of the USGS. Using multiple correlation, Mr. Potter establishes correlation between peak rate of runoff per unit area for a 10-yr frequency and four independent factors. These factors are area of watershed, a topographic factor involving length and slope of the principal stream (which implicitly involves the shape of watershed), and two rainfall factors. The two rainfall factors involve the intensity of rainfall for a 1-hr duration, the annual amount of rainfall, and the number of excessive storms, as these vary geographically within the region. The relationships between these five variables are expressed in an equation. For forty-one of the fifty-one watersheds this equation gave peak rates of runoff which varied by not more than 25% with those derived directly from the runoff measurements. For other regions, further studies indicated that not only will the relationships

shown in the equation change, but also the number and character of the independent variables may be different from those found to be significant for the Allegheny-Cumberland Platéau.

This type of study has great potentialities, not only in enabling the highway engineer to make a reliable estimate of probable peak rates of runoff for ungaged streams, but also in developing a basic understanding of hydrology. Certain regions may be found to have sufficient stream-gaging stations because of uniformity of characteristics, and in others the wide, unexplained deviations from the regional trend will indicate a need for installation of additional gaging stations.

On small, agricultural watersheds Mr. Potter has shown that land use is a significant factor affecting peak rates of runoff, particularly where one kind of land use covers the entire watershed.[13] Studies have not shown any significant correlation of peak runoff with land use on the larger watersheds in the Allegheny-Cumberland Plateau study.

[13] "Surface Runoff from Agricultural Watersheds," by W. D. Potter, *Research Report No. 11-B*, Highway Research Board, Washington, D. C., 1950.

Small Watersheds

In analyzing the data on peak rates of runoff obtained by the SCS from experimental watersheds in Maryland, Ohio, Wisconsin, and Nebraska (as reported by Mr. Potter[13]), it was found that these peaks may be approximated by a single runoff curve to be adjusted by certain factors. This curve, shown in Fig. 5, gives the peak rate of runoff that may be expected to be equalled or exceeded on the average of once in 25 yr on mixed-cover watersheds in the humid section of the United States in localities where the rainfall factor is 1.0. The map in Fig. 6 shows values of the rainfall factor east of 101° west long. The factor is not given to the west of this meridian because of extreme local variations in rainfall intensity and also because the application of the basic runoff curve to the western part of the United States has not been verified.

The factors for land use in the table of Fig. 5 are given for three classifications of land slope. Those for slopes greater than 2% are derived from the SCS data[13] and are reasonably reliable. The factors for flat and very flat land slopes are estimates based on the effect of slope in increasing surface detention and channel storage, and are therefore subject to correction when observed data become available. The frequency factors are based on the SCS report cited by Mr. Potter.[13] It should be noted that these factors are the same as those found applicable to rivers in Kansas. The term "mixed cover" deserves some explanation. The term is used to describe land use on a watershed with cultivated land, pasture, and woodland. This factor should be used wherever the watershed is not predominantly in one type of cover.

The effect of soil type on peak rates of runoff has not been clearly established. For a longer frequency—such as 25 yr—the peak runoff probably occurs when the soil is nearly saturated by antecedent rainfall and, except for very pervious soils which can drain freely, the peak rate of runoff is assumed not to be affected by soil type. For more frequent floods it is likely that peak rates of runoff will be higher on the more impermeable soils.

Fig. 5 provides, for the humid portion of the United States, a simple method

for estimating peak rates of runoff for use in the hydraulic design of culvert waterways for drainage areas of less than 1,000 acres. The close agreement of Fig. 5 with Fig. 3 suggests that the runoff curve can be extrapolated to larger drainage areas, although land-use factors will not apply. Unfortunately very few runoff data from which the curve might be extended are available on watersheds from 2 sq miles to 200 sq miles in area. If the curve is projected beyond 1,000 acres as a straight line, the land-use factors should converge on that for mixed cover. On larger watersheds the effect of channel storage does not cause differences in peak runoff caused by land use.

Mr. Potter has clearly demonstrated that the rational method of estimating peak rates of runoff is not applicable to agricultural watersheds because the runoff coefficient varies widely depending on the condition of the watershed when the storm occurs.[13] The maximum runoff corresponding to a given rainfall intensity may therefore have a frequency of once in 25 yr where the rainfall frequency may be only once in 5 yr.

Highway departments of a number of states are cooperating with the USGS in the financing of gaging stations on watersheds with areas of less than 200 sq miles. Some of these are recording stations and others are crest stage gages. These stations must be maintained for at least 10 yr so that the length of record will constitute a sufficient sample for determination of regional flood frequency characteristics on watersheds in this size range.

Conclusions

Statistical analysis of peak runoff records for a period of years is a logical approach to estimating floods, because the runoff record has automatically integrated all the conditions effective on a given watershed. Many of these factors cannot be measured directly, and if they could it would still not be possible to anticipate the probability of any given combination of values of the variables. The regional flood-frequency curves demonstrate a close correlation between peak runoff for a given frequency and the size of the drainage area in a given region. Further studies will disclose the principal factors causing departure from the mean curve for a region, and may indicate reasons for differences between regional curves. Small agricultural watersheds with a given land use and area have peak rates of runoff which correlate significantly with regional rainfall intensities. When peak runoff for mixed cover on small watersheds is expressed as a function of the drainage area size, the relationship is closely similar to that found for much larger watersheds in Kansas.

Maximum floods of record in Kansas show no well-defined relation to the size of the drainage area because the probable frequencies extend over a wide range. Consequently, the design of bridge waterways on the basis of maximum floods alone is a less satisfactory procedure than giving consideration to the probable frequency of a flood. The regional flood-frequency curves provide a method for ascertaining whether the maximum flood of record is an extreme event for which provision for maintenance of highway traffic cannot be justified on economic grounds, or is a flood which can be expected to occur frequently enough to justify provision of sufficient waterway to pass the entire flood without excessive backwater. High water elevations on the unobstructed stream, even if accurately established, are not adequate for determination of bridge

waterways, since the amount of backwater caused by the contracted opening depends on the flood discharge rate as well as the stage.

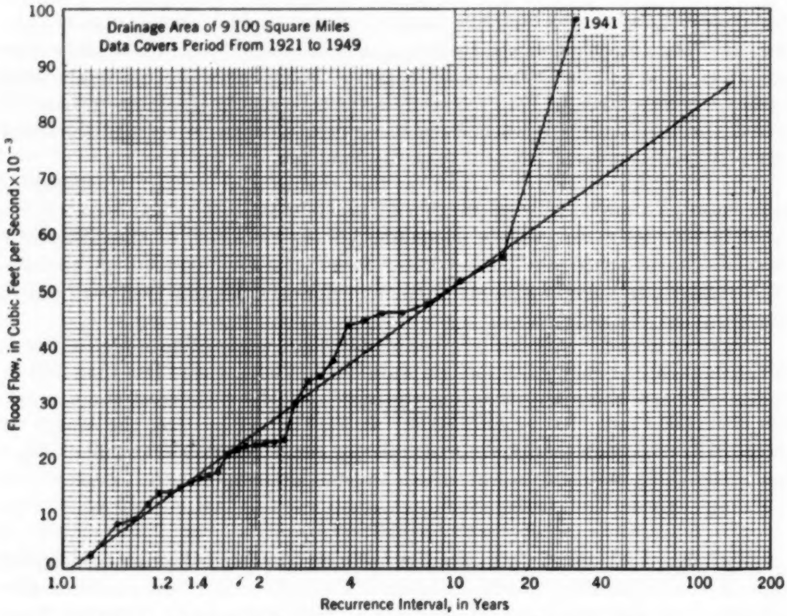


FIG. 1.—FREQUENCY CURVE FOR BIG BLUE RIVER AT RANDOLPH, KANS.

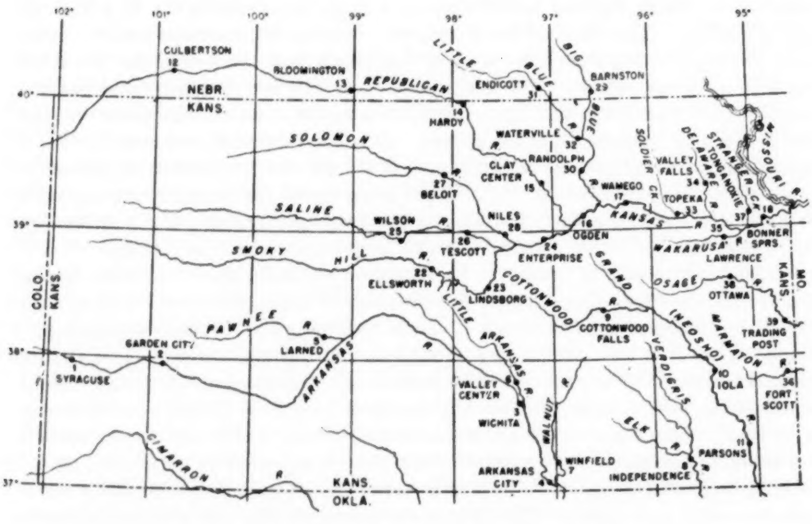


FIG. 2.—LOCATION OF STREAM GAGING STATIONS IN KANSAS

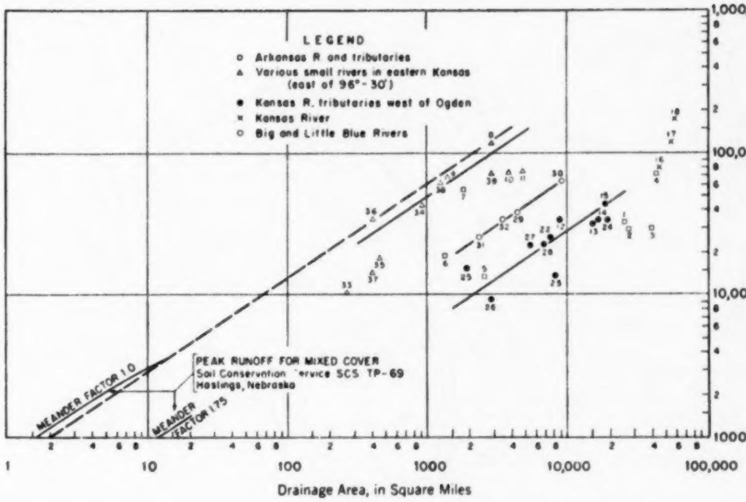


FIG. 3.--25-YR FLOODS IN KANSAS

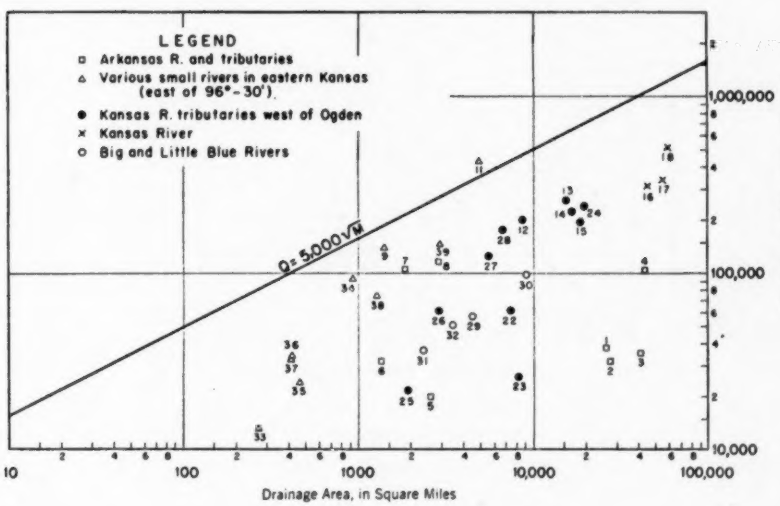


FIG. 4.—MAXIMUM FLOODS OF RECORD IN KANSAS

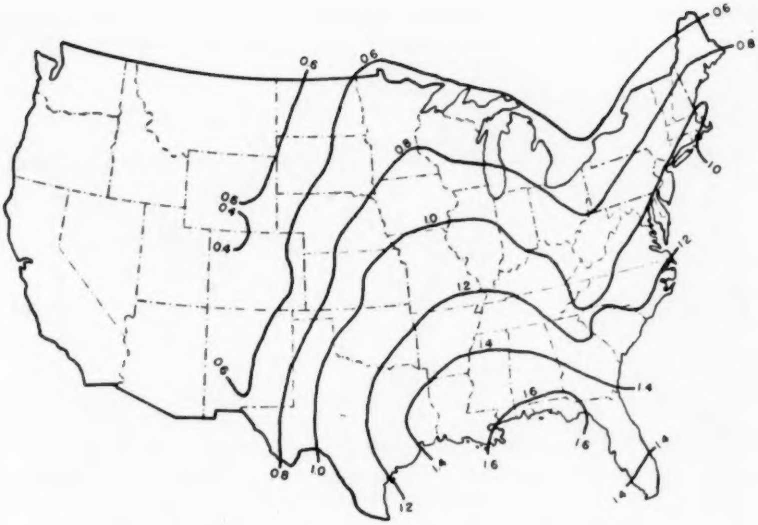
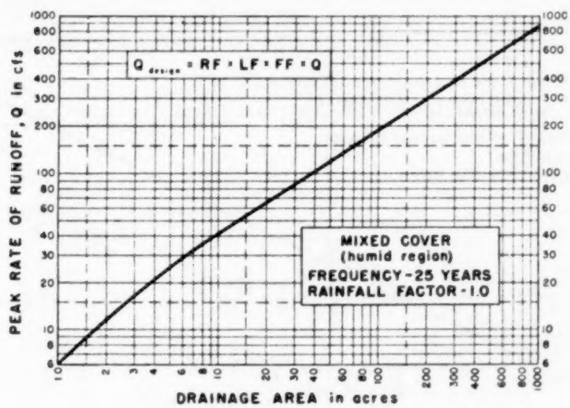


Fig. 5.—Peak Rates of Runoff for Watersheds of Less Than 1,000 Acres



RAINFALL FACTOR (RF) See Figure 6

LAND USE AND SLOPE FACTORS (LF)

Land Slope	Steep over 2%	Flat 0.2%	Very flat, no ponds
100% Cultivated (row crops)	1.2	0.8	0.25
Mixed cover	1.0	0.6	0.2
Pasture	0.6	0.4	0.1
Woods, deep forest litter	0.3	0.2	0.05

FREQUENCY FACTORS (FF)

Frequency, years	5	10	25	50
Factor	0.6	0.8	1.0	1.2

Fig. 6.—Map of the United States Showing Rainfall Factors